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Renewable energy powered membrane technology: A leapfrog approach to rural water treatment in developing countries?

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ABSTRACT

Lack of access to safe drinking water remains a present concern in many developing countries, particularly in rural locations. Membrane water treatment technologies have the potential to remove microbiological and chemical contaminants reliably and simultaneously from a wide range of water sources. When powered by renewable energy, these systems are autonomous and have the ability to 'leapfrog' over installation of traditional infrastructure for electricity and water supply to reach remote communities. In this paper, current estimated costs for water, membrane plants and infrastructure are compared to indicate the window of opportunity for these exciting renewable energy powered membrane (RE-membrane) technologies. General estimated costs for decentralized membrane systems are within the range of some untreated water costs in developing countries. Specific system costs, however, are very process and location dependent. The appropriateness of a successful approach thus depends partially on careful examination of these parameters. In view of the comparisons made here, the biggest hurdle to adoption of the RE-membrane technology in a remote location may not be cost, but rather sustainability issues such as the lack of skilled personnel for operation and maintenance, service networks, availability of spare parts, socio-economic integration and adaptive capacity of communities to transfer and develop technology appropriate to local needs and circumstances.

Contents

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1. Provision of safe drinking water in developing countries

Renewable energy powered membrane (RE-membrane) systems are attractive decentralized water treatment options in areas without infrastructure and where dissolved contaminants render water sources unsafe [1,2]. Such technologies are suitable to treat most sources, including wastewater and seawater, to meet potable water standards and are scalable from single household to city-scale supplies. A key challenge is the lack of infrastructure in remote areas, which are often rural areas of low population density, regions affected by conflict or natural disaster, in either developed or developing countries. In fact, according to the report by the World Health Organisation (WHO) and United Nations (UN) [3]: '*more than three quarters of those who lack access to safe drinking water and basic sanitation live in rural areas.*' This is set against the backdrop where [4]: '*Alternative water systems have been used in rural areas for decades. They obviously are an option in new urban areas where no central infrastructures pre-exist, and in extra-urban urban areas.*' Such alternative supplies cover water reuse in addition to decentralized treatment. Water reuse is receiving significant attention, in particular at large scale and as a competitor to seawater desalination, but its uptake is slowed significantly by public acceptance [5]. While the urban, peri-urban and rural situations differ in population density, water governance and propensity of pollution, the country to country differences can be significant. For example a small village in rural Africa may consist of a population of about 50, while a classic Indian village may have a population of up to 5000. This emphasizes the requirement for scalable models and technologies.

Poor water quality (microbiological and chemical) is the cause of unnecessary health problems within communities [6–8]. While advanced technologies such as RE-membrane systems are technically capable to address this severe problem [9–10], the acceptance is neither as broad nor the implementation as rapid as expected. Systems rarely survive long term in such regions. In addition, it is a common perception that such technologies are too costly, too complicated and hence generally unsustainable for application in developing countries. Eskaf and Moreau [11] have highlighted the lack of financial and managerial capacity due to the higher unit costs of small systems and lower revenues and skill available in rural areas, while Bugaje noted that addressing energy availability in Africa was the key to addressing health, educational and other socio-economic problems [12].

Interestingly, the above issues are not limiting technology uptake in other markets. In the field of mobile communications technology, adaptation evolved differently. Fifteen years ago few, if any, would have foreseen the mobile phone boom in developing countries. Growth in mobile phone subscription in Africa increased between 2000 and 2011 at a compound annual growth rate (CAGR) of 41%, significantly higher than in Europe (30%) [13]. In contrast, whereas over 92% of households in the UK had a fixed phone line in 2013 [14], the African continent has the lowest coverage of fixed phone lines: just over one line per 100 people in 2011 and only growing at a CAGR of less than 3% [13]. With the mobile phone boom, the African continent has leapfrogged over the western industrialization pathway of fixed telecommunication lines, and in doing so saved on considerable investment in infrastructure. In addition, the rapid adoption of phones contributes significantly to economic development in areas such as (i) agriculture trading: receiving market prices via short message service (SMS); (ii) enabling the transfer of small amounts of money from one person to another via SMS; (iii) enabling climate change adaption by using the global positioning function of the device to map out deforestation in Malawi; (iv) training healthcare workers in rural areas of Mali via telemedicine [13], and (v) the payment of water and electricity usage in East Africa.

The success of the mobile phone may inspire a similar decentralized approach to water services in rural areas in developing countries. In remote locations that are lacking both water and electricity infrastructure and a safe water point source, installation of RE-membrane technologies could avoid the reliance on centralized treatment works. The promise of such advanced membrane systems, namely contaminant removal, modular design, technical robustness, upscale potential, was outlined by Schäfer et al. [15] and Peter-Varbanets et al. [10]. In this paper, water costs by source in developing country contexts, typical membrane plant costs and estimates of infrastructure costs are compared to indicate the window of opportunity for this leapfrog approach. The context is set by a discussion of water supply and quality in developing countries, and an introduction to membrane water treatment technologies.

Lack of safe water supply is a recognized problem in many developing countries. Globally, it is reported that 884 million people do not have access to safe, protected water sources [16]. This has a significant economic impact [17], and causes illness and death from easily preventable water-related diseases. For example, "*88% of diarrheal disease – the second leading cause of death in children younger than five years after respiratory illness – is attributed to unsafe drinking water*" [6]. Global policy supports efforts to increase coverage of safe water supply, with a target within the UN millennium development goals (MDGs): to, "*halve by 2015 the proportion of people without sustainable access to safe drinking water*" [18]. Whilst trends indicate that globally the world has already met this target, the progress of individual countries varies greatly. In particular, only 19 out of 50 sub-Saharan African countries are on target to meet his goal and rural areas lag well behind [18]. Furthermore, the issue of dissolved contaminants (including salts), that are difficult to remove, remains vastly unaddressed.

Progress of the MDG for improving access to 'safe' drinking water is measured against the number of people having access to an 'improved' water source [18]. The following are classified as 'improved' sources: piped water into a dwelling, yard or plot, public tap or standpipe, tubewell or borehole, protected dug well, protected spring, and rainwater [19]. It should be noted that this does not consider actual water quality. By definition, an 'improved' drinking water source or delivery point, "*…by nature of its construction and design, is likely to protect the water source from outside contamination, in particular from fecal matter*" [20]. There is no direct link, however, between an 'improved' water source and the quality of that source; the 'safety' of 'improved' water sources may be compromised by factors such as inadequate treatment at a centralized treatment works, recontamination in the distribution system, contamination of a well or borehole from anthropogenic sources (for example mining, farming, sewage), or the natural chemical quality of groundwaters with naturally high levels of salt or contaminants such as fluoride, nitrate, uranium or arsenic). Thus, even in cases where a community has access to an 'improved' water source, that source may require treatment to make it 'safe' for drinking. The WHO and United Nations Children's Fund (UNICEF) Joint Monitoring Programme (JMP) for water supply and sanitation notes that [16]: *"any new target set beyond 2015 will have to address water quality, which will have to be measured or estimated in a meaningful and cost-effective manner"*. This is precisely where RE-membrane systems play a key role in treating such waters to potable standards.

Indeed there has been a lot of discussion in the literature on RE-membrane technologies (see for example [1–2,21–22]). The majority of these papers focus on a review of the possible technologies, which is often weighted towards large scale installations as that is where the majority of the technical and financial data originates from. In addition, the challenge of installing and operating such technologies in small isolated communities is often not discussed.

Providing rural areas with access to 'safe' water evidently remains a major challenge, with 53% of people in rural sub-Saharan Africa still

Fig. 1. Various sources of untreated water in Ghana, (A) trucked water supply (B) surface water collection (C) Handpump for wells and bores, (D) protected dug well, (E) rainwater collection and (F) standpipe.

using water from ‘unimproved’ water sources [16]. These sources (unprotected spring or dug well, cart with small tank/drum, tanker truck, surface water) are more likely than ‘improved’ sources to be contaminated by microbiological contaminants (bacteria, viruses, parasites) from human and animal excreta, in addition to chemical contaminants such as nitrates and phosphates from farming activities and sewage seepage. Those consuming this water incur a significant risk of developing the associated adverse health effects [23–24].

Water supply mechanisms in urban or peri-urban areas typically include municipal supply from centralized treatment works or small town water supplies. These may provide water via private household connections or public standpipes. Pollution can be a significant problem, especially in peri-urban settings. When municipal supplies fail due to overstretched distribution systems or poor maintenance, alternative sources such as contaminated point sources, or in some cases water tankers, vendors (for example kiosk, hand carter, water bearer) or packaged water (bottle/plastic bag) may be sought [25]. In addition to environmental concerns over packaged water, quality is usually regulated by food, not water guidelines and generally highly variable.

In rural and remote areas, low population densities make the installation of centralized water systems economically unfavorable. Consequently, water is usually directly drawn from groundwater (wells, boreholes), rainwater or surface water as pictured in Fig. 1. In some cases, the time-demands of drawing water in these ways can hinder education and development of women and girls in particular, because they retain the main responsibility for water ‘transport’ [26]. As with the urban situation, water supplies in rural areas may be supplemented from water tankers, vendors or bottled water, although this generally decreases with distance from urban centers.

2. Cost of water, electricity, and related infrastructure in developing countries

The cost of water in developing countries can be surprisingly high (see Table 1), especially when compared to costs in industrialized countries – for example, 1.3 US$/m^3 in America and as high as 4.3 $/m^3 in Denmark [29]. This price range is in the same order of magnitude as the cost of water from household connections in Africa ($<$0.1–2.7 $/m^3) [32], despite the disparity in wealth between continents. However, average water use in developing countries is much lower than that in Europe (typically between 150 and 350 l per person per day) or Australia and North America ($>$500 l per person per day) [30], which affects expenditure on water. For example, in Mozambique, Uganda and Ghana

Table 1
Indicative cost of water in sub-Saharan Africa by source.

Source	JMP Category	Cost ($/m^3)		
		Ghana [a] [31]	23 African Cities [b] [32]	Tanzania [c] [33]
Surface water	U	Free	–	–
Well	–	Often free	–	–
Household connection	I	–	< 0.1–2.7	0.3
Borehole	I	0.1–1.4	–	–
Standpipe	I	0.1–1.4	0.5–9.4	–
Household reseller[d]	–	–	1.0–3.4	1.3
Water tanker	U	5.6–6.7	2.4–9.7	7.5–10.0
Water vendor[e]	–	–	1.7–11.4	4.4–12.5

JMP=Joint Monitoring Programme, I=Improved water source, U=Unimproved water source.

[a] Data based on data collected from 220 communities throughout Ghana. Currency conversion uses a ratio of old Ghanaian Cedis (GHC)/US dollars (USD)= 0.0001 (2007 average) [34].

[b] Data based on surveys of government officials and utility staff in 23 African cities.

[c] Data from Dar es Salaam, Tanzania.

[d] Indicates the resale of water from a household connection.

[e] May indicate a stationary vendor such as a kiosk, or a mobile distributor such as a hand-carter or water bearer.

Table 2
Estimated costs of water pipe material and installation in selected countries. Data for Ghana and Kenya is unspecified regarding pipe diameter and inclusion/exclusion of installation cost.

Country	Pipe detail	Unit price ($/km)	Ref.
Scotland	110 mm MDPE (SDR 11)	7605–8771	[34]
Scotland	110 mm MDPE, Installed – grass	99,574	[34]
Scotland	110 mm MDPE, Installed – rural/suburban	153,633	[34]
Scotland	110 mm MDPE, Installed – urban	186,456	[34]
Sri Lanka	80 mm DI	38,027	[35]
Sri Lanka	90 mm uPVC (600)	12,323	[36]
Ghana	Unspecified, PVC	450	[36]
Kenya (KIWASCO)	Unspecified, PVC	1,990	[36]
Kenya (NWASCO)	Unspecified, PVC	62,540	[36]
Tanzania	80 mm DCI, pipe only cost	31,500	[37][a]

MDPE=medium density polyethylene, SDR=standard dimension ratio, DI=ductile iron, uPVC=unplasticized polyvinyl chloride, DCI=ductile cast iron, KIWASCO= Kisumu Water and Sewerage Company, NWASCO=Nanyuki Water and Sewerage Company.

[a] Currency conversion TZS/USD=0.00066 [38].

the estimated average water use is respectively 4, 15 and 36 l per person per day [30], which is below the water poverty threshold. In fact, WHO and UNICEF recommend a minimum of 20 l/day from a source within 1 km for drinking and basic personal hygiene [16]. At this point it is worth noting that household connections in developing countries do not often reliably deliver safe drinking water.

In the open (unregulated) market, water prices can become excessively expensive. In Ghana, for example, the cost of water via tanker truck was observed to range between 5.6 and 6.7 $/m^3 [31]. Additionally, in a survey of African cities, water vendors were found to be charging between 1.7 and 11.4 $/m^3 [32]. The observed variability in cost may be due to differences in availability (geographical and seasonal), distance from source, and profit margins. It is conceivable that the prohibitively high price of water from resellers makes free, 'unimproved' water sources a more attractive option for low income consumers, particularly during dry seasons when the lack of rainwater, and slower recharge of wells and boreholes put a higher strain (and potentially a higher cost) on water resources. Ultimately the cost is driven by market and 'willingness to pay' [8]. In areas where waters are contaminated this raises the question if such waters could be treated economically to offer a safe supply.

Infrastructure in rural areas illustrates a negative synergy between lacking access to water and energy. Both water and electricity infrastructure are expensive, and as population densities decrease away from urban centers, the investment cost per capita increases. At a critical distance, the cost of conveying water from a centralized treatment works to an outlying community will become comparable with the capital cost of installing a decentralized community-based water treatment system. For the purpose of this paper, some water and electricity infrastructure costs have been collected, and will be compared with the cost estimates of autonomous membrane treatment systems in the next section. Approximate costs available for water pipe installation in different countries (not including operational pumping or treatment costs) are presented in Table 2. Costs for boreholes have not been included as those will need to be considered locally and depend on the drilling depth required and the nature of the subsurface.

Actual installation costs depend on the nature and accessibility of terrain, local labor costs, contractor fees, pipe diameter, proximity to the supplier, and both quality and availability of tools. Additional 'pipecosts' data for African countries is available from the African Infrastructure Country Diagnostic (AICD) database [36]. Values per meter of polyvinylchloride (PVC) pipe recorded in the database range from 370 $/km for the National Water and Sewerage Corporation Uganda and 590 $/km for the Dar es Salaam Water and Sewerage Corporation, Tanzania to 78,410 $/km for the Nkana Water and Sewerage Company, Zambia. Even within the same country the reported cost can vary greatly between utility companies. For example, pipe costs in Kenya are reported to be 1990 $/km (Kisumu Water and Sewerage Company) and 62,540 $/km (Nanyuki Water and Sewerage Company). The inclusion or exclusion of installation costs is the most likely reason for the vast disparity between high and low end costs reported, together with accessibility of terrain. The high-end costs are in the same order of magnitude to those of Scotland and Sri Lanka while a reasonable range may be $10,000–$20,000, about 25% of the costs to install an unpaved road. Further detailed data including rates for different diameter pipes and breakdown of costs for installation is not the objective of this work. The cost effectiveness of centralized (grid connection) versus decentralized (renewable) energy supply is an analogous scenario to that for water supply. Estimates for electricity grid extension and connections per distance are shown in Table 3.

Nässén et al. [40] estimated life cycle costs for rural electrification in northern Ghana, comparing grid extension to distributed power generation from photovoltaics. Capital cost of gridlines in Ghana were estimated to be 14.9 $/m^3 for medium voltage (MV) lines (33 kV) that would extend electricity supply to a community, and 21.1 $/m^3 for low voltage (LV) lines (240/415 V) that would be used to construct a community micro-grid. Although the costs here are somewhat dated, an independent figure published in 2012 of 22 $/m for transmission lines [41] is in agreement to the figures from a decade earlier [40]. These costs included three-phase lines, poles, transformers and labor. As with water distribution, the cost of electricity infrastructure is found to vary widely, with LV lines reported in the literature to cost between 5 $/m and 33 $/m^3 [40].

Table 3
Estimates for electricity grid extension and connections per distance.

Cost element	Cost ($)		
	Sri Lanka [39]	Botswana [39]	Ghana [40]
Meter and installation	27	175	
Additional poles[a]	50	80	
LV cable per meter	0.16	7.5	
LV gridline (total cost)[b] per meter			21
MV gridline (total cost)[b] per meter			15

LV = low voltage (240/415 V), MV = medium voltage (33 kV).

[a] Additional poles are required for service connections of more than 30 m.
[b] Total cost includes three-phase lines, poles, transformers and labor.

Table 4
Electricity prices from conventional and renewable technologies. The regions/countries covered in the four columns are: (i) the 34 member countries of the Organisation for Economic Cooperation and Development (OECD); (ii) Renewable Energy Policy Network for 21st Century (REN21) – regions specified, if not then global indicative cost; (iii) the data for Bazilian et al. is for the USA; (iv) for Europe.

Technology	Description	Cost ($/kW h)			
		OECD[a] [42]	REN21[b] [43]	Bazilian et al.[c] [44]	EU energy portal[d] [45]
Photovoltaics (PV)		0.22–0.60			
	Residential		0.20–0.46 (OECD) 0.28–0.55 (non-OECD) 0.16–0.38 (Europe)	0.16–0.25	
	Commercial			0.16–0.31	
	Utility		0.12–0.38 (OECD) 0.9–0.40 (non-OECD) 0.14–0.34 (Europe)	0.10–0.18	
	Solar home system 20–100 W		0.40–0.60 (rural)		
Hydro	0.01–1000 kW		0.05–0.40		
Wind	Offshore	0.10–0.19			
	Onshore	0.05–0.16			
	Small turbine < 100 kW		0.15–0.20 (USA)		
	Household turbine 0.1–3 kW		0.15–0.35 (rural)		
Biomass	Gasifier 20–5000 kW		0.08–0.12 (rural)		
Gas		0.07–0.11			
	Domestic price 30,000 kW h/year				0.05–0.15
Nuclear		0.03–0.08			
	Village-scale mini grid		0.25–1.00		
	Domestic price 3500 kW h/year				0.11–0.35

[a] Levelized cost of electricity (LCOE) with 5% discount rate.
[b] Levelised indicative costs.
[c] Calculated from global PV market prices for systems based in both cloudy and sunny climates.
[d] End-user prices reported in Europe, currency conversion (2009 average) EUR/USD = 1.43 [38].

The current comparative costs of grid electricity and renewable sources are presented in Table 4. Cost depends on source, scale, and also on government policies which can affect costs with incentives and subsidies. Currently the cost of residential photovoltaic (PV) solar power (0.16–0.25 $/kW h) in most cases is slightly more expensive than the price of conventional grid electricity in Europe (0.11–0.35 $/kW h). However, in some countries like Italy and Cyprus, "grid parity" has already been reached with PV, meaning that solar power costs the same, or less than, the *retail* price of electricity from typical large scale generators (coal,

gas, nuclear) [46–47]. Policies and subsidies can affect such costs significantly (in either direction), however energy fuels mined from natural resources can be expected to increase in accordance with the limited availability of those resources. Conversely, the costs of renewable energy, particularly PV, can be expected to fall due to decreasing production costs and increasing installed capacity while technologies and markets mature. A very recent study determined that the levelized cost of electricity (LCOE) from grid-connected PV in Kenya was 0.21 $/kW h and noted that this was already cheaper than the price from Kenya's expensive conventional power plants, such as diesel generators and gas-turbines, both which account for a large share generation [48].

It is difficult to consider extension of grid supply solely for the purpose of powering a water treatment system. Where a local grid supply exists, the cost of connecting to it is more easily estimated, taking into account the costs of LV cable, poles, transformers and labor. Longer distance connections, however, are likely to be achieved as part of a bigger rural electrification program to provide several communities, centers, or households with electricity. However, energy provision remains a large cost contributor to the capital cost of small-scale water treatment systems and the availability, reliability and cost of electricity are paramount.

3. Small-scale water supply membrane technologies

Dissolved contaminants require advanced technologies, in particular when several contaminants co-exist and water quality varies seasonally. Membrane-based water treatment systems are capable of removing several contaminants simultaneously and reliably [49]. The technology is scalable from systems using individual modules to large scale water supplies for mega cities (see Fig. 2) and process selection can be adjusted to any water quality and desired contaminant removal.

Membrane technology comprises microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) that are pressure-driven processes, whereby different contaminants are removed by predominantly sieving while other mechanisms such as charge repulsion or sorption can play a role. In general the driving pressure is provided by pumps although MF and UF may also operate under gravity (a pressure head). Electrodialysis (ED) works on the principle of removing charged species via the use of ion selective membranes and electrodes to apply DC electric potential. Membrane distillation (MD) is a thermally driven process whereby water vapor permeates the membrane, leaving behind non-volatile contaminants in the feed solution. The contaminants that can be removed with different membrane processes are summarized in Table 5. UF offers physical disinfection (pathogen removal) whereas hybrid sorbent coupled with UF, as well as the processes of NF, RO and MD, may simultaneously remove additional contaminants such as fluoride, arsenic and other dissolved species. Processes can be coupled in hybrid configurations.

Typical operating conditions, recoveries (percentage treated water with respect to feed water quantity) and costs for membrane treatment are summarized in Table 6. The energy required to operate water supply membrane systems depends on the power requirements of the driving force (pressure) and auxiliary equipment. The full energy consumption is normally expressed as specific energy consumption (SEC) in kW h/m^3, which together with electricity supply cost ($/kW h) can be used to estimate an energy cost per m^3 of water produced. Energy is a dominant and highly variable factor in the cost of water treatment.

Reported costs of membrane processes are situation-dependent and hence cannot be considered a solely intrinsic cost of a particular

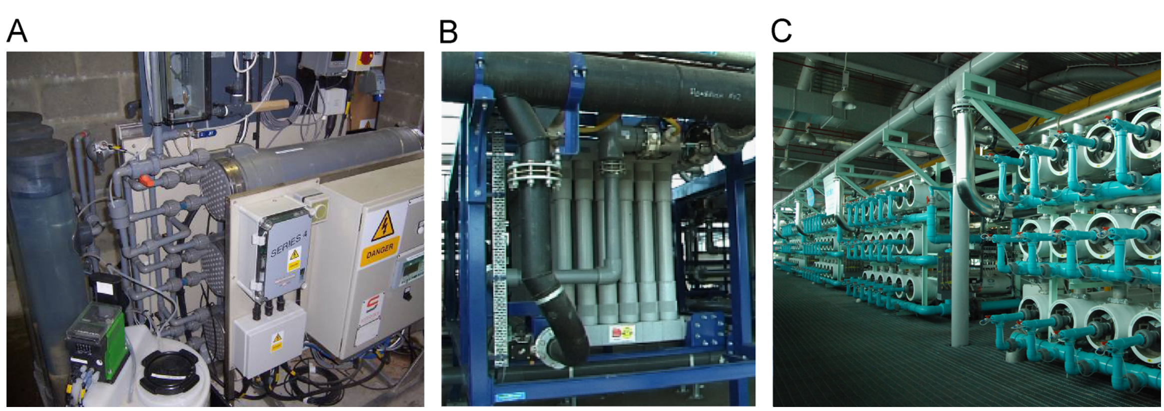

Fig. 2. Scalable from small village to megacity: membrane systems for water treatment. (A) Small nanofiltration plant in Scotland, (B) medium scale microfiltration cassette and (C) large scale reverse osmosis unit.

Table 5

Indicative rejection of contaminants by different water treatment membrane processes (● usually high removal, ⦿ partial removal, ○ no removal).[a]

Membrane process		Contaminant to be removed							
		Particulates (e.g. clays)	Bacteria	Colloids/ nanoparticles	Viruses	Macromolecules	Multivalent ions	Monovalent ions	Micropollutants
MF	Microfiltration	●	●	⦿	⦿	○	○	○	○
UF	Ultrafiltration	●	●	●	●	⦿	○	○	○
NF	Nanofiltration	●	●	●	●	●	●	⦿	⦿
RO	Reverse Osmosis	●	●	●	●	●	●	●	●
ED	Electrodialysis	○	○	○	○	○	●	●	⦿
MD	Membrane Distillation	●	●	●	●	●	●	●	⦿

[a] Actual contaminant removal depends on specific membrane characteristics which vary between different manufacturers (characterization and testing of specific products recommended).

Table 6
Typical operating conditions and production costs for membrane processes (recovery is the fraction of clean water produced per raw water treated).

Process	Typical operating pressure (bar)	Recovery (%)	Typical costs[a] ($/m^3)	Capacity (m^3/day)	Ref.
MF	0.3–0.5	90–98	0.7	38	[50] [c]
			< 0.2	19,000	[50] [c]
			0.2–0.4	8–151	[51]
UF	0.3–0.5	90–98	0.7	38	[50] [c]
			0.2 O&M	3100	[52]
			< 0.2	19,000	[50]
NF	5–10	75–95	0.2–0.8 O&M	70–550	[53] [c]
			0.3 O&M	2400	[54]
			0.2–0.3	10,200–15,500	[55]
BW-RO	15–30	< 90	5.6–12.9	< 20	[56]
			0.8–1.3	20–1200	[56]
			0.1–0.4	10,000–500,000	[57]
SW-RO	55–70	25–45	1.5–18.8	< 100	[56]
			1.3–3.9	250–1000	[56]
			0.7–1.7	1 000–4800	[56]
			0.7[b]	65,000–240,000	[58]
	Driven by				
SW-ED	-potential difference	85–94	4.7	5.5	[59][c]
			0.2 O&M	2200	[60]
SW-MD	-heat (+sometimes vacuum)		0.9–1.0 O&M	24,000	[61]

BW = brackish water, SW = seawater, O&M = cost specified as operation and maintenance only.

[a] Factors used to calculate costs vary in the literature and are not always specified. In particular, some include investment (capital) cost to give a total water cost, whereas others report operation and maintenance (O&M) cost only.

[b] Average of seven Spanish desalination plants following a full cost analysis.

[c] N.B. Although these references are quite dated and cost data should be interpreted with caution, they are still included for completeness.

process (Table 6). Scale, water quality, membrane type, pressure requirements, energy source and costs, required chemicals and their transport, as well as salaries for maintenance are all important factors that determine the actual costs. Some general trends can, however, be elucidated: (1) costs fall as capacity increases, for example, a seawater (SW)-RO plant with capacities in the range < 100 m^3/day exhibit a high cost of 1.5–19 $/m^3, however this drops markedly to 0.5–0.7 $/m^3 for plant capacities > 100,000 m^3/day [53]; (2) operating costs are energy dependent, for example, NF requires a lower operating pressure and hence has a lower SEC than RO. Bellona et al. determined that a halving in the cost associated with electricity consumption could be achieved via substituting RO modules with NF modules in a large-scale system [55]; (3) treatment costs decrease with lower salinity feedwaters (water quality permitting). This is easily seen with brackish water (BW)-RO plants where small-scale (20–1200 m^3/day) and large-scale (> 40,000 m^3/day) plants produce water at a cost of 0.8–1.3 $/m^3 and 0.3–0.5 $/m^3, respectively [53]; (4) higher product water quality or lower feed water quality requires more costly treatment, for example a large-scale treatment plant equipped with RO modules would cost 20% more than if it was equipped with NF modules [55] (in addition to the increased electricity consumption mentioned in point 2 above); (5) newer emerging technologies such as MD and ED typically cost more than the more established pressure-driven membrane processes [60,61], and (6) membrane fouling and management thereof (pre-treatment, cleaning and membrane replacement) needs to be considered [62].

Despite the general trends noted, it is very difficult to establish actual costs and determine which technology is more cost effective than another. Partly, this is due to variations in reporting costs in the literature, where different authors include or neglect different cost contributors, and partly due to lack of comparable data. In addition, economic comparisons are difficult due to the contribution of varying local factors (energy provision, maintenance requirements, feedwater quality, operational particulars, and auxiliary systems) and the difference in feed and product water qualities. In absence of data from broad technology uptake experience, such costs will need to be estimated on a case by case basis and adjusted with long term maintenance experience.

Water treatment technologies may be applied at centralized, household or community level. The technologies are treating water to a safe standard. It should be noted here that keeping water clean following treatment is a matter of distribution system management and hygiene. Those matters need to be managed appropriately. Access to safe water is a first step towards increased hygiene [63]. Centralized systems are the most common option in urban and peri-urban areas, where high population densities and economies-of-scale favor centralized solutions for the supply, distribution and treatment of water [10]. A current trend is to extend distribution systems to towns and villages at proximity of urban centers. This has limitations due to the costs of installing infrastructure, as investigated in this paper. In addition, as the water quantity is often insufficient for continuous supply, regularly empty pipes and lack of positive pressure pose water quality maintenance challenges as well as microbial regrowth issues. In consequence, decentralized systems are often the only way to improve water quality from contaminated sources in rural and remote areas.

Peter-Varbanets et al. [10] have conducted an excellent review of the wide range of household and community level water treatment options that exist, including boiling water with fuel, solar disinfection, adsorption, chemical disinfection, sedimentation or settling, ceramic filters and sand filters. The effectiveness of such household water treatment in poor populations has been debated [64,65]. A number of household-level membrane-based treatment systems also exist, such as the Lifestraw® products [66] and GE-Homespring [67]. Since Lifestraw® and Homespring are based on UF, these systems are successful in removing microbiological contaminants, but not capable of removing salinity or other dissolved chemical contaminants such as fluoride, nitrate or arsenic. It is not the intention of this work to review all of the treatment options again, but instead to highlight the opportunities for small membrane filtration systems, which exhibit a number of advantages over other technologies: (i) the ability to remove particles, viruses, bacteria, salt ions and trace contaminants; (ii) the high productivity of $>1\ m^3$ per day, suitable for a community; (iii) RO and ED are the most energy efficient desalination technologies for high and low salt concentrations, respectively [68]; which (iv) makes the technologies very suitable for coupling with RE technologies for deployment in remote areas.

Community water systems, as defined by the US EPA, serve a minimum of 25 residential customers year round, while those classified as small serve up to 3300 residential customers [11]. The capacity of small-scale, community-level systems is typically 0.1–10 m^3 per day, enough to treat drinking water for several families or a small village [10]. The modular nature of membrane systems means that capacity may easily be increased to serve a larger village, isolated community, or provide more water per person. Considering economies-of-scale, Hinomoto [69] determined that the cost minimum of water utilities is at a capacity between 15,000 and 19,000 m^3 per day. On the other hand, a 2004 study estimated that 15–30% cost reductions of on the unit cost of water produced could be realized simply by doubling the system size [70]. These would indicate that the costs for small systems will be disproportionally high.

Community-level membrane systems have been adopted successfully in remote areas of countries such as Scotland where the first NF plant was installed at Lochgair in 1992 [71]. The success of this led to the installation of 82 membrane filtration plants (capacities range from 3 to 50,000 m^3 per day) in remote Scottish locations since 1994 [71]. These systems were employed to remove organic matter and cryptosporidium. The operation and maintenance (O&M) of such remote treatment systems is both challenging and expensive. In developing countries, community-level membrane treatment has been limited typically to emergency situations or to urban areas where they may be employed in touristic resorts, bottling facilities, hospitals or hotels [72]. This is may be surprising given the suitability of the technology for remote locations and reasons for this lack of adaptation may be ill-informed cost perceptions and bias towards the 'free and simple' technologies that may not perform medium-long term, in particular with regards to dissolved contaminant removal. On the other hand the difficulty of O&M is unresolved and this is a weak part of aid where 'Insufficient funding for O&M undermines the sustainability of services in a major way [3]. Eskaf and Moreau [11] have proposed a shared management approach to save costs through economies of scale achieved through regionalization. Such approaches are equally applicable in developing countries. A recent pilot study of solar desalination technologies in Namibia [73] will be discussed later as a detailed case study.

4. Renewable energy powered membrane filtration systems

There are many reasons for the partnering of RE technologies with membrane filtration [74]. Firstly, RE microgenerators are designed to last for 20 years in relatively harsh environments. Some technologies, such as PV, require very little maintenance due to the lack of any moving parts and manufacturers typically provide warranties of 25 years. Solar technologies are also very well-matched to the load; with solar panels produce more power in areas that receive more sunshine, at times when the population are likely to consume more drinking water. Furthermore, both membrane modules and solar panels are modular in nature, thus enabling the system to be resized at a later stage to meet increased future demand. It has been demonstrated that RO systems can operate effectively without energy storage [75], while efficiencies can be higher since the generated electricity is used instantaneously and no longer needs to be stored and later retrieved from a battery bank. Thus, such a PV-RO system would only run in the daytime and no noise is generated to disturb people at night. Furthermore, the elimination of batteries also reduces any risk of chemical spills and, by nature, no pollution is produced during the operation of the system. Thus, a strong foundation exists for RE-membrane systems to provide a sustainable solution for clean water provision in remote areas.

In the absence of reliable water and electricity infrastructure, achieving autonomous operation is desirable. For water treatment such autonomy can be gained by providing the required process energy by RE [74,76], while MF and UF may also be simply driven by gravity (pressure head) if no auxiliary equipment is required. Fluctuations may be beneficial or detrimental to system performance, however intermittent operation leading to system shut downs is not desired [75]. Supercapacitors can be used to control short span energy fluctuations and avoid frequent system shut downs and possibly mechanical damage [77]. Water pressure and flow increase with more energy being available [78]. This may compromise performance and ultimately damage membranes. Fluctuations of pressure and flow may be beneficial for fouling control. More research and development is required to establish safe operating windows of such systems and control their operation within this regime. A key advantage is that following initial investment, energy production from RE sources incurs minimal operational costs. For PV systems, the ongoing operational costs have been determined to be 47 \$/kW-year [79] (with any excess power being used for other purposes such as cooking, lighting, and charging electrical appliances such as mobile phones), whereas for centralized grid generators the cost of electricity is driven more equally by both capital (electricity infrastructure, connection charge, generator cost) and operation cost (electricity supply charges or operation, maintenance and fuel for a generator). While several systems are on the market, long term operation and socio-economic integration remains vastly unresolved. Local preferences and conditions need to be considered, which may include taste or lack thereof [80]. Testing technology in rural areas has been greeted with both curiosity and enthusiasm. Some examples of this are shown in Fig. 3, ranging from a bench-scale sorbent+UF system designed removing fluoride in northern Ghana in 2010 (Fig. 3A) to small-scale UF/NF hybrid filtration system ($\sim 1\ m^3$/day) that was tested in the Australian outback in 2005 (Fig. 3B and C).

So far, the biggest application of RE-membrane systems has been in desalination. An overview list of small-scale PV-powered RO membrane filtration systems including operation costs was published by Ghermandi and Messalem [81]. In addition, integration of renewable energy (solar, PV, wind, biomass, geothermal) with membrane desalination processes (MD, RO, ED) have been extensively reviewed [1,2,22,82,83]. Eltawil et al. [2] comment that in spite of their recognized advantages, RE-powered desalination systems are scarce and currently limited to 0.02% of the total desalination capacity. While this is normal for emerging technologies, the reasons for this are attributed to [2]:

(i) availability – areas suffering from water stress are not always endowed with a suitable RE resource;

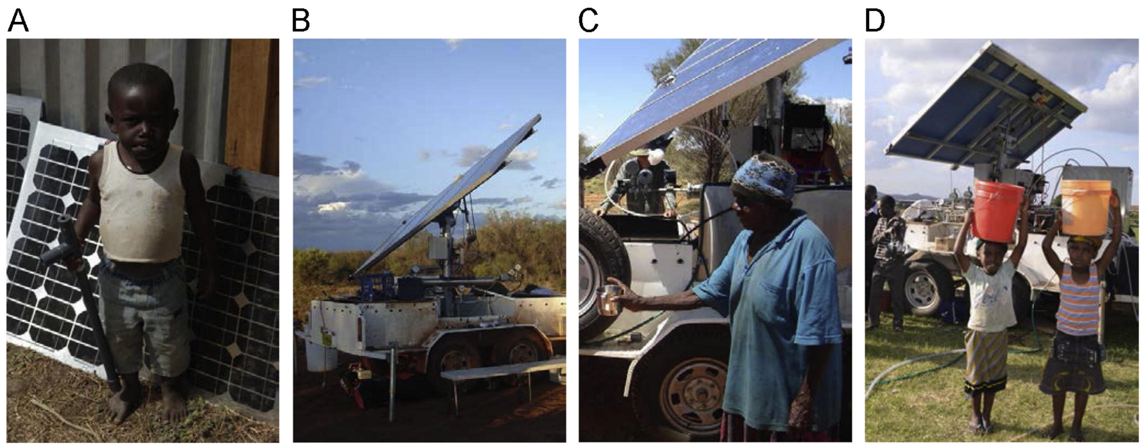

Fig. 3. Renewable energy powered membrane systems. (A) UF module for laterite sorbant separation in Ghana, (B) transportable PV-powered UF/NF hybrid membrane filtration system, (C) water testing in Australian outback after brackish groundwater treatment, (D) community demonstration of fluoride removal in Tanzania.

Table 7
Examples and indicative costs of membrane systems powered by renewable energy.

Process	Power	Description	Cost estimate ($/m^3)[a]	Ref.
UF	Gravity head + PV (for water lift)	Skyhydrant™ commercial system with normal capacity between 20 and 200 m^3/day. Operates under 0.5–4.0 m differential pressure (0.05–0.4 bar). Capital cost $3500. Costing based on 10 year lifetime.	< $0.50 per person per annum	[84]
SW-RO	PV	3 m^3/day capacity, batteryless system tested at lab scale. Capital cost $33,200. SEC 3.2–3.7 kW h/m^3.	2.9	[85]
SW-RO	Wind	10.4 m^3/day batteryless prototype tested at lab scale with preliminary results. Capital cost $50,820.	1.2	[86]
SW-RO	PV + wind	1.5 m^3/day capacity system with batteries installed in Tanzania. Capital cost $47,950.	9.9[c]	[87,88]
BW-RO	PV	5–7.5 m^3/day capacity system with batteries, pilot study in Oman. Capital cost $98,040. SEC 2.3 kW h/m^3	6.5	[89]
Activated carbon + MF-RO	PV + wind	20 m^3/day capacity system with batteries installed in ecovillage in South Africa, treating recycled waste water. Capital cost $43,855[b].	2.2	[90]
BW-UF + NF/RO	PV	1 m^3/day capacity, batteryless system "ROSI" field-tested in Australia. System lifetime unknown. Capital cost $15,840.	5.9	[15,91]
ED	PV	2.8 m^3/day capacity system. Feedwater approximately 1 mg/l TDS. Requires ion exchange prior to ED due to radon and arsenic content of water. SEC 0.82 kW h/m^3. Estimated plant life unknown. Capital cost approximately $10,150	16	[92]
MD	PV	0.1 m^3/day capacity installed in Irbid, Jordan. Brackish feedwater. Capital cost $7695	15	[93]

[a] Unit cost is in $/m^3 based on 20 year lifetime unless unit or lifetime are otherwise specified.
[b] End-user price from South African supplier, currency conversion (Oct 2007) ZAR/USD = 0.1253 [38].
[c] Cost includes annual service contract over assumed system life of 20 years.

(ii) cost – the capital costs remain high for both RE and desalination technologies;
(iii) technologies – the combination of desalination and RE systems needs to be compatible (normally not an issue with electrically-driven desalination systems); and
(iv) sustainability – the infrastructure and technical support are lacking.

Adoption in developing countries will naturally be slower where technology adaptation to local requirements (low-cost, appropriate maintenance, robustness, business generation) is also a key factor.

'Setting the prices right for water is the first step towards stimulating markets for alternative water systems when they are needed' [3]. The cost of RE-powered small scale membrane systems is affected by a large number of parameters including energy type, membrane type, system capacity, feed water quality, location, the use of batteries, and the maturity of the technology. As the acceptance of PV and membrane based-technology continues to increase, costs continue to fall. During the 1990s capital costs of membrane plants were reported to have halved, whilst operational costs also fell because product life expectancies were increased [71]. However, it is difficult to find meaningful cost data in the literature for small RE-membrane systems that have been actually installed in the field. This is due to novel nature of the technology with only a small number of studies being published, and the often unique set-up of each system. A summary of some published costs are shown in Table 7. A clear absence of long-term operating experience and hence cost should also be noted.

RE-ED and RE-MD are observed to cost considerably more than the pressure-driven membrane processes, however, it should be noted that these are younger technologies at an earlier stage of development. Unfortunately, no data was available for RE-UF, however since several UF systems are available on the market and the costs of these are expected to be considerably less than for RE-RO, due to the significantly reduced energy costs (< 10%) of UF compared to RO [9]. Capital costs comprise roughly one third

contributions each from installed membrane, RE source, and system auxiliaries. One important conclusion to note here is that the capital costs (between $15,840 and $98,040 for the RE-RO systems in Table 7) are within the cost range of infrastructure for remote locations. For example, installing 10 km of water mains could cost in the region of $19,900 in Kenya or $123,230 in Sri Lanka (Table 2). The point at which the capital cost to extend coverage of water mains far exceeds that of installing a community-based membrane treatment system will vary with scale and local conditions and would thus need to be determined on a case by case basis.

Operating costs of membrane systems (see Tables 6 and 7) are also lower than some of the reported water costs in Africa (Table 1). For example a 38 m^3/day UF system may cost 0.7 \$/m^3 to run, or a 70 m^3/day NF system could cost 0.8 \$/m^3, but the important point here is that these values are comparable to a household connection in an African city ($<$0.1–2.7 \$/m^3) or water obtained from a public standpipe in Ghana (0.1–1.4 \$/m^3). The open water market in particular (for example, 1.0–3.4 \$/m^3 from a household reseller) can make the operating cost of membrane systems look very favorable. Nevertheless, it cannot be assumed that all people choose (or are able) to pay for water, and it is likely that many villagers use free water sources or occasionally buy small amounts of water for consumption purposes only. This will stretch the resource further and may result in a far more sustainable approach than what developed country are accustomed to, where some 50 l/person/day of highly treated water is used to flush toilets [30].

In consequence, cost may not be as big a barrier to implementation as is traditionally thought. Of course, the cost of water treatment by membrane processes is more expensive than many of the low-cost household treatment technologies promoted by many non-governmental organizations (NGOs). The effectiveness of membrane treatment, however, is extremely high and may justify a bigger investment on the grounds of water quality and reliability where the removal of specific contaminants is required. Government policies supporting these technologies could offer incentives or subsidies that make this investment more affordable. In summary, there is definite promise in certain locations for small-scale membrane treatment technologies to make an effective alternative to the expansion of centralized treatment works and distribution infrastructure.

5. Potential barriers to implementation: operation and maintenance

Membrane treatment technologies have many design advantages over classical water treatment systems. They are able to reliably remove pathogens and other contaminants, are scalable to the required production capacity, are adaptable to the nature of the feed water, have the potential to operate in the absence of grid electricity and have a comparably small physical footprint. Peter-Varbanets et al. commented that [10], "*…there are good prospects for decentralized systems based on membranes, but a need exists for research and development of systems with low costs and low maintenance, specifically designed for developing countries*." Roark et al. [94] consider the role of O&M in rural water supply projects to be *"synonymous with sustainability"*. The O&M of small treatment systems can be a challenge in remote areas of developed countries such as Scotland, in less developed countries it remains an issue of grave concern. Clearly a need for effective and appropriate management strategies persists. Key issues towards long term sustainability that need to be addressed in further research, development and deployment plans are listed and then discussed below:

- Training and retention of skilled operators;
- water quality monitoring;
- system failures;
- technology adaptation and public awareness;
- finance; and
- sustainability.

These issues are highlighted in several reports in the literature as being key for the successful implementation of a small-scale water treatment system in a remote area [10,94,95].

Skilled operators are required to install, maintain and operate systems. Operational arrangements for a rural community may be difficult, with the required skills difficult to find and even harder to retain. Van der Vleuten et al. [96] noted that for the effective maintenance of solar home systems in Africa, there was a definite lack of trained technicians. Indeed, in Algeria it was observed that a few years after installation, the lack of well-trained operators had resulted in several small-scale desalination plants operating at far below their optimum [21]. The WHO observed that the O&M of small water systems is typically undertaken by community members with [97]: (i) limited specialist skills, who (ii) can only commit a small amounts of time, and often receive neither (iii) financial reward, nor (iv) formal training. One possible solution is to train illiterate rural men and (particularly) women as people who are more likely to remain in the community. The Barefoot College in Tilonia, India has been very successful in training more than 37,000 men and women to work as 'barefoot' teachers, doctors, midwives, solar engineers, water drillers and engineers, hand pump mechanics, architects, artisans, masons, water chemists, phone operators, and in a number of other skilled roles. Villagers, often women, attend college and return to their communities with materials and skills [98]. The growing network of 'barefoot professionals' in India and beyond is transforming rural communities and stands as a stellar example of capacity strengthening that may impact significantly upon the successful adaptation of new technologies. The case study in Section 6 will give an example of how simple maintenance and repairs can be performed at the village level, but these caretakers need to be supported by a formal service structure that is operated by the system supplier.

Water quality monitoring can be expensive and is rarely part of a management plan for small water treatment systems and, as a consequence, the malperformance of systems often goes unnoticed. Gambier et al. [99] have demonstrated that acceptable water quality from a small RO desalination plant can be guaranteed – even during the occurrence of faults – by implementing a model predictive control algorithm. However, significant effort is still required to implement these laboratory developments into a robust system that can operate autonomously in the field. The case study discussed in more detail below will provide an indication to the concept that is put in place in order to maintain and operate a solar-powered desalination plant in Namibia [73].

System failures need to be promptly identified and dealt with to assure uninterrupted supply of water. Common failures in membrane systems are (1) fouling of membranes that results in reduced water productivity and requires backwashing or cleaning, (2) damage of moving parts (pumps, valves) and (3) failing sensors and electronics [100]. Kelkar et al. [101] noted that although RO technology was successfully proven to operate in a rural Indian environment, the management of these desalination plants was difficult. However, there are also examples of robust systems, with a gravity-fed UF plant installed in rural South Africa for treating surface water recently demonstrating nearly autonomous operation, with the sole operational requirement being to remove the build-up of material in the membrane vessel by emptying on a daily to weekly basis [102]. Ray and Jain [103] emphasize the need for spare parts for drinking water treatment systems to be

available within a remote community. Ideally, a supply chain to provide replacement parts is developed, with the number of parts to be stocked being reduced significantly by using standardized parts and compatible systems. In the interests of long term sustainability and innovation, there is a preference for systems to be manufactured locally using locally accessible skill and materials. While in some countries this is underway (such as China and India), in others more capacity needs to be created. Locally manufactured systems and maybe eventually even membranes, the supply of any chemicals required for pre- or post-treatment should be investigated. In order to ensure correct O&M, a form of service contract may be an option when individual systems are supplied. In this manner, the supplier takes responsibility for service coverage as well as ensuring the supply of water in the long term. There are examples in the area of mobile communications and solar electricity, where the successful development of local capacity for service, support, and maintenance of such systems has been realized [104].

The basic need for safe water has to be recognized within the communities and valued as a life-sustaining element, rather than other desired items. Demonstration of health benefits and impact on quality of life wants will stimulate a willingness to pay and reduce the perceived cost barrier. There exists a large barrier of limited public awareness about RE technologies in sub-Saharan Africa, which is underpinned by the high levels of illiteracy [96] as well as the lobby for conventional water treatment systems. A continuous assessment and monitoring of what works (and what does not work), needs to be in place to be able to adjust small treatment systems to the requirements of local conditions. This includes the operation and management strategy in addition to social acceptability. Peter-Varabanets et al. [10] found that the social acceptability of point-of-use membrane filtration systems in developed countries range from positive to negative, depending on the region studied, and hence this remains a challenge for developing countries. Importantly here, information needs to be published as detailed case studies that address failures in an open and transparent manner and facilitate more rapid learning.

A direct correlation exists between higher product water quality, higher energy requirements and treatment costs. Therefore, the public awareness also needs to extend to the notion of have a dual water supply system, with a small volume for drinking water only, while washing and irrigation water is supplied from alternate sources. While treatment systems will save many lives, if failures occur and result in health issues then responsibilities and indemnities need to be clear. For small water systems this remains unresolved and needs to be addressed, although the WHO's view is that it is the responsibility of the community-based small system operator for ensuring water quality as part of a water safety plan (WSP) [97]. Current discussion on private water supplies may provide guidance. In general though, there is often a lack of political will in sub-Saharan Africa to make the necessary decisions to enable improved planning and policy [105]. Thus, a private sector approach is likely to be required for early adopters.

The issue of cost has been addressed in great detail in the previous sections, and although membrane technology is becoming increasingly efficient and costs are decreasing significantly, the technology remains unaffordable for the rural populations of developing countries [10]. For the case of RE technologies, Suberu et al. noted that sub-Saharan Africa possesses the poorest levels of financial investment in the whole world [105]. Appropriate funding models – as opposed to ongoing aid handouts – local investment and returns, enterprise facilitation, and ultimately financial independence is the road to development. Encouragingly, both Koch and Caradonna [104] and the OECD [106] identify many avenues that can be pursued by developing countries in order to further the deployment of green technologies in their economies. On a community scale, there have been successes with schemes such as tiered pricing, shared use approaches, and micro-financing [103]. Papapetrou et al. [107] suggest that cooperation between water provision and energy supply companies could assist RE-powered desalination to take off. In the case of Africa, one suggestion is that there needs to be a far greater number of public–private partnerships in order to effectively realize the water services required in remote areas [108].

Eskaf and Moreau [11] have suggested a regionalization model where several communities will work together in sharing resources for management. This is very applicable to development since if the same technology was deployed to a region, critical mass will be created that warrants a joint operational manager, local maintenance support, and a store for spare parts and other strategies that would not be cost effective for single communities. According to Roark et al. [94], a multi-tier approach is often required for successful system maintenance, in rural locations, with the different tiers comprising the community (basic operation and preventative maintenance), local/district mechanics (repairs), and the government (for example providing mobile teams for complex tasks). The relative involvement of each of these three tiers is defined by local factors, meaning that the ideal management model is community-specific. Some of the key issues affecting this model (the balance/involvement of different tiers) include the capacity of traditional community organizations, key community skills, complexity of technology, availability of spare parts, requirements shared with other sectors (for example, irrigation), capacity of private sector, standardization and local manufacture of equipment, national and regional economies, strength of government agencies and staff, government policies and legislation [94]. Within this framework, success also requires innovative integration mechanisms, sound operator training, realistic costing of service, inclusion of women in decision making (as the main users of water points), and ethical behavior of suppliers. Such approaches can address the concern of the WHO [3] that due to a lack of maintenance expenditure progress on MDGs may reverse. Wood et al. [109] outlined strategies to enhance acceptance of water treatment at household level, and many such measures can be adapted to small treatment systems.

The sustainable integration and adaptation of membrane water treatment systems in rural communities is a challenging task. The successful use of these systems in tourist resorts, bottling facilities and hospitals in many developing countries, however, demonstrates that maintenance of the technology is entirely feasible in such locations, provided a financial incentive exists. In addition, the first commercial-scale UF membrane production facility in Africa was commissioned in 2010 [110], indicating that the market potential for these systems is recognized locally. Whilst the necessary supporting structures for O&M of membrane water treatment systems in rural locations may not be available today, reaching a critical mass in the number of systems installed will rapidly improve this situation.

As an example, Grundfos is partnering with local organizations, and has integrated the company's solar-powered groundwater pumping expertise together with a mobile phone based payment system, as well as integrated remote monitoring (income, water volume pumped, pump status, and service alarms) and an integrated after-sales service contract [111]. Over the last few years, nearly 40 of these 'Lifelink' systems have been installed throughout Kenya and are providing drinking water in remote areas at a cost of about 1.15 $\$/m^3$ [112]. Grundfos outline many lessons learned from the Lifelink project [111], however two of them are particularly pertinent for RE-powered water treatment systems as well: (i) *"High-tech innovative solutions can and should be applied to improve the living conditions of the world's poor and create sustainable development"*, and (ii) *"Contrary to most experience in the development sector […] it is indeed possible to provide a sustainable, self-financing, and transparent model for management and maintenance of water projects, even in remote rural areas."*

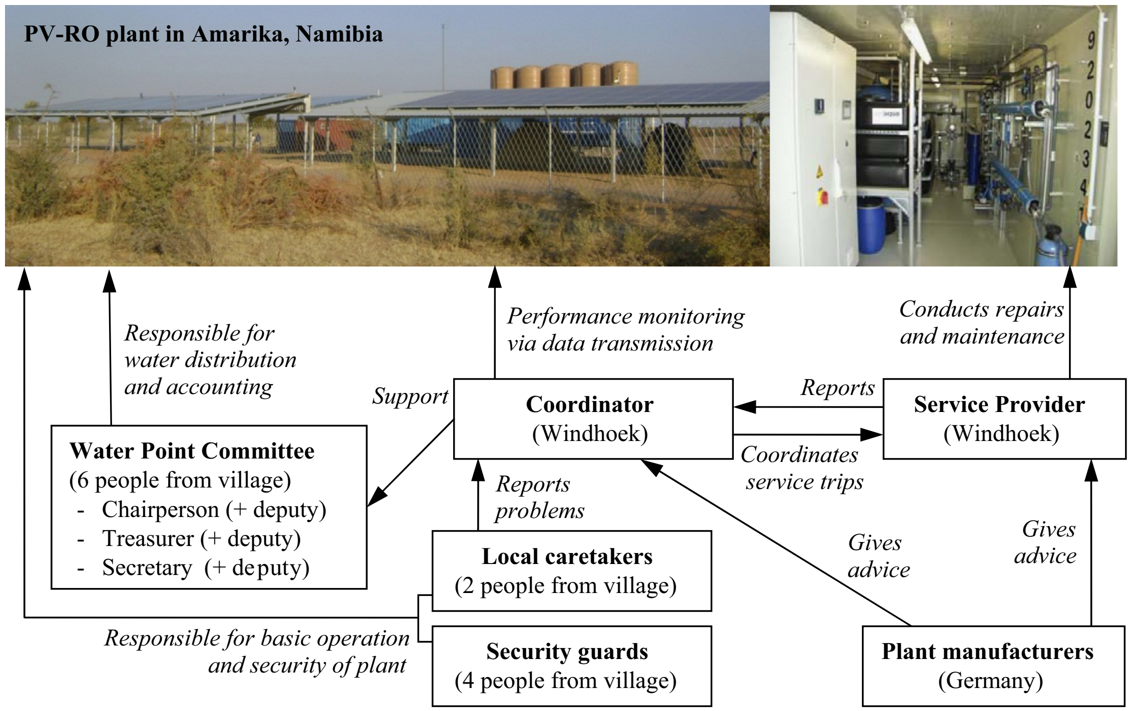

Fig. 4. Schematic diagram with overview of operational concept implemented in the CuveWaters' solar desalination plants in northern Namibia (adapted from [114]; photos reprinted with permission from Marian Brenda, TU-Darmstadt, Germany).

6. Case study – solar desalination in northern Namibia

An interesting case study for solar-powered desalination systems can be found in northern Namibia, near the Etosha salt pan, which receives an annual average rainfall of 470 mm and an annual average daily solar irradiance of >6 kW h/m². Here, a German–Namibian project "CuveWaters" [73,113–116], has installed four different solar desalination pilot plants in the Omusati region in the villages of Amarika (population 370, feedwater salinity 23,000 mg/l as total dissolved solids (TDS)) and Akutsima (population 250, feedwater salinity 5,000 mg/l as TDS) in July 2010. The roads in this region are poor, and there is no electricity, mobile network, or piped water connections. As of July 2012, the operation of the plants was taken over by the Namibian Ministry of Agriculture, Water and Forestry. In Amarika, the chosen technologies are PV-powered RO (with battery-backup) and solar-thermal membrane distillation, while in Akutsima two non-membrane evaporative-based solar thermal systems were installed.

The PV-RO plant in Amarika is interesting in that no chemicals are proposed for the pretreatment process. Conventional RO system design may use chemicals: (i) coagulants for removal of colloids (flocculation); (ii) anti-foulants to prevent growth of microorganisms on the membrane (biological fouling); and (iii) anti-scalants avoiding formation of salt crystals on the membrane. Since it is not always easy to ensure a constant supply of chemicals in a remote area, the new development here is to produce chemicals from the feedwater directly using electrochemically-driven scale remover. This process enables free chlorine to be produced for disinfection, as well as reducing the magnesium and calcium levels in the water to prevent scaling. No information is available about the chlorine tolerance of the membranes. Two other pre-treatment filters are used – one based on gravel and another on activated carbon. After that, the feedwater is pumped through an RO membrane at a relatively high pressure of 30 bar, required due to the very high salinity.

The power for the system is provided by a 19.8 kW$_p$ PV array and a large battery bank (48 V, 1500 A h) enabling 24 h operation. The required daily electrical energy for the PV-RO system is about 30 kW h, and other electrical loads for Amarika (23,000 mg/l TDS) are also powered from the PV system. The system produces an average of 3.3 m^3 of permeate (980 μS/cm or approximately 640 mg/l TDS) per day from 14.1 m^3 of feedwater [114] at 23% recovery, 97.2% retention, and with a SEC of 9.1 kW h/m^3. Even though an energy recovery turbine is utilized, the SEC remains high due to three main factors: (i) the high feedwater salinity, (ii) the relatively small size of the plant, (iii) the energy consumption of the scale remover, and (iv) electrical losses introduced by the batteries. The 10.8 m^3 of concentrate was disposed of via re-injection wells and an evaporation pond [114].

The operation of the solar desalination plants are summarized in Fig. 4, adapted from the original schematic in Brenda et al. [114]. The water point committee (WPC) consists of six people, who are elected from the community and receive no salary. The WPC are responsible for the plant, including sales and distribution of the water. The local caretakers are trained and are based at the plants daily to keep them in good running order. If there are problems with the plant the caretakers then contact the coordinator. There are four security guards the site, who are elected by the community and get paid for working night-shifts. The site is fenced off and nothing was stolen during the two years of the pilot phase, which is credited to the guards as well as the community, who have a strong sense of ownership of the plants due to their involvement in planning, construction and operation. The service provider is a Windhoek-based company who was initially trained by the system manufacturers during the installation phase and has since gained extensive experience in maintenance and repair over the following two years. The service provider remains in contact with the manufacturers of the plants via satellite phone, and are also responsible for taking samples for water analysis. There is also a service technician based in Oshakati ($\sim$100 km away) who can repair most mechanical and electrical components and visits the

plants typically once every two months. The plants' manufacturers monitor performance via satellite data transmission and advise the service provider regarding fault determination. Problems were typically detected quicker via data transmission than via the caretakers. In addition, having direct access to the data can assist with trouble-shooting and can therefore make service trips more efficient. The coordinator from the Directorate for Water Supply and Sanitation Coordination (DWSSC) coordinates service of the plant and is responsible for their sustainable operation. The coordinator receives information about problems occurring and decides how to respond, as well as paying the service provider for repairs and maintenance.

The dynamic prime costs – defined as the capital cost, calculated with a system lifetime of 20 years and a 5% interest rate, as well as replacement spare parts and consumables – of the four desalination systems are in the 5.5–14 $\$/m^3$ range. Given this range covers four very different solar desalination technologies, the PV-RO plant has not been included in Table 7. The annual O&M cost for the PV-RO plant over the first two years was estimated to be $13,000, with 70% of the costs attributed to labor and travel [114]. Thus, while long term experience is still required to determine failure rates and spare parts requirements over the system lifetime, the O&M expenditure could be significantly reduced if several plants are clustered within a defined service area.

Overall, the CuveWaters project demonstrated that it is possible to install and operate small solar-powered desalination plants in a remote area of sub-Saharan Africa [114]. Among the challenges that need to be overcome are: (i) a general lack of infrastructure; (ii) limited accessibility, especially during the rainy season; and (iii) a lack of skilled staff that are permanently on site. Valuable experiences were gained by all involved during the two year pilot phase. The weakest link in the operational concept was the WPC with the members not taking responsibility and the fluctuation of membership being high. It was suggested that the WPC receive more support from the current owners (DWSSC), whose officers should visit the plants once a month. In addition, further operator training sessions would be beneficial for the local caretakers – both enhancing their skill level and also reducing O&M costs significantly. Regarding cost, the manufacturers learnt a lot about adapting systems to Namibian conditions and therefore the frequent servicing that was required in the first few months after start-up would not be required again. In next phase of the CuveWaters' project [116] a better understanding of the O&M costs will be gained as well as refinements to the operational concept – for example, a system will be implemented that transforms the data from the plants into simple status reports that are sent to the coordinator on a regular basis. In addition, the long term suitability of the brine disposal methods (re-injection wells and evaporation pond) need to be evaluated.

7. Conclusions: a leapfrog approach to rural water supply?

Advanced treatment is required when water is unsafe due to dissolved contaminants. Small-scale membrane systems powered by renewable energy can provide an autonomous treatment option for rural areas. Such RE-membrane systems are able to reliably treat many water sources to meet drinking water standards. The often-lacking infrastructure and increased local water prices make a compelling case for their consideration as an alternative to the installation of expensive centralized infrastructure for water and electricity. The costs for decentralized membrane systems are within the range of some 'improved' but untreated water costs in developing countries. Specific system costs, however, are very process and location dependent and hence this requires careful consideration in the relevant context. The appropriateness of the leapfrog approach described here depends on careful examination of multiple parameters and there is unlikely to be a one-size-fits-all solution. When current costs of infrastructure and untreated water are investigated, it can be noted that the cost of 'advanced' technologies such as RE-membrane systems may not be as big a barrier to implementation of drinking water systems as is traditionally thought.

Instead, the biggest hurdles to employment of these technologies in remote locations are sustainability issues such as the lack of skilled operators or infrastructure for O&M, robustness of the technology, service networks, availability of spare parts, and adaptive capacity of communities to transfer and develop technology specifically suited to local conditions. In many instances, it may not be sensible for a developing country to follow the model of industrialized nations for supplying drinkable water from a centralized treatment works. Instead, it may be more appropriate to supply drinking and washing water separately. In areas without single distribution systems in place such options exist and must be considered, in particular given the rapidly emerging problem of micropollutants globally that require more and more advanced treatment. The development of innovative approaches to manage water provision and small water treatment systems in particular are required for rural areas worldwide. In sub-Saharan Africa, there are examples of successful solar-powered water supply schemes and, more specifically, the case study in Namibia is an example which has demonstrated that this concept can be extended to incorporate water treatment. Thus, the first step on the path to the realization of a financially, environmentally, and socially sustainable provision of clean drinking water in developing countries using solar-power has been demonstrated.

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